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Designing an intelligent system to predict drill wear by using of motor current and fuzzy logic method

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ABSTRACT. In automation flexible manufacturing systems, tool wear detection during the cutting process is one of the most important considerations. This study presents an intelligent system for online tool condition monitoring in drilling process. In this paper, analytical and empirical models have been used to predict the thrust and cutting forces on the lip and chisel edges of a new drill. Also an empirical model is used to estimate tool wear rate and force values on the edges of the worn drill .By using the block diagram of machine tool drives, the changes in the feed and spindle motor currents are simulated, as wear rate increases. To predict tool wear rate, fuzzy logic capabilities have been used to develop an intelligent system. The simulation results presented with MATLAB software show the effectiveness of proposed system for on-line drill wear monitoring. This is confirmed by comparing the measured and estimated values with each other in which the value of R^2 was obtained 0.9367 in the regression graph.

Keywords: tool condition monitoring, current signal, machine tool drives, thrust and cutting forces, drill wea, fuzzy logic.

Concepção de um sistema inteligente de predição do desgaste da broca usando corrente do motor e método de lógica fuzzy

RESUMO. Na automação de sistemas de manufatura flexível, a detecção de desgaste da ferramenta durante o processo de corte é uma das mais importantes considerações. Este estudo apresenta um sistema inteligente para monitoramento on-line de condições da ferramenta em processos de perfuração. Neste artigo, modelos analíticos e empíricos foram usados para predizer o impulso e forças de corte nas extremidades labiais e do cinzel de uma broca nova. Um modelo empírico também foi utilizado para estimar a taxa de desgaste da ferramenta e os valores de força sobre as extremidades da broca desgastada. Ao utilizar o diagrama de blocos das unidades da ferramenta, as mudanças na alimentação e nas correntes do motor de fuso são simuladas à medida que a taxa de desgaste aumenta. Para predizer a taxa de desgaste da ferramenta, a lógica fuzzy foi empregada para desenvolver um sistema inteligente. Os resultados da simulação apresentadas com o software MATLAB mostram a eficácia do sistema desenvolvido para o monitoramento on-line do desgaste da broca. Isto é confirmado pela comparação entre os valores observados e estimados com cada um, no qual o valor obtido de R^2 foi de 0,9367 no gráfico de regressão.

Palavras-chave: monitoramento das condições da ferramenta, sinal de corrente, unidades de máquina-ferramenta, forças de impulso e de corte, desgaste da broca, lógica fuzzy.

Introduction

For monitoring of machining operations, the measuring techniques have traditionally been categorized into two approaches: direct and indirect. In the direct approach the actual quantity of the variable, tool wear, is measured. Examples of direct measurement in this case are the use of cameras for visual inspection, radioactive isotopes, laser beams, and electrical resistance. Through indirect measurement approaches, auxiliary quantities such as the cutting force components can be measured (TETI et al., 2010).

Recent attempts have concentrated on the developing of the methods based on indirect monitoring (ALIUSTAOGLU et al., 2009, RIVERO et al., 2008; ZHU et al., 2009). Among direct methods, the most widely used method is optical method.

There is a basic problem with this method that machining process must be stopped during measurement of the wear (GHANI et al., 2011; RIVERO et al., 2008). Therefore, to solve this problem, indirect methods were developed. In these methods, tool wear monitoring is performed by measuring variables such as tool vibration, cutting force, acoustic emission, motor current etc.

Among indirect methods used for detecting tool condition, motor current sensing is a major one. The major advantage of using the measurement of motor current to detect a malfunction in the cutting process is that the measuring apparatus does not disturb the machining process. Moreover, it can be applied in the manufacturing environment at almost no extra cost (XIAOLI et al., 1999). Some researchers measured the spindle and feed motor current to estimate the static torque and thrust, in order to detect tool condition (PAL et al., 2009; SEVILLA-CAMACHO et al., 2010; VERL et al., 2009).

In on-line tool wear monitoring, there are two methods to obtain the values of feed and spindle motor currents during drilling process: (i)developing an analytical model; (ii) measuring the current directly from the motor. By the methods based on analytical models, first, the values of cutting and thrust forces for a new drill are predicted by models, then the value of thrust and cutting forces of the worn drill is predicted by using of analytical and empirical models. Finally, the values of motor currents required for the drilling process are obtained based on the thrust and cutting forces of the worn drill, via by using of block diagram of machine tool drives. For investigating the results, the drill wear values obtained for the certain amount of motor current are processed by decision support system like fuzzy logic or neural network.

In this paper, first, analytical models for thrust and cutting forces in drilling are simulated and validated by experimental results. Then, tool wear model is simulated by using of forces, as input values of block diagram of the wear model. Thereafter, the block diagram of the machine tool drives are simulated and current transition behavior for spindle and feed motor, are shown, comparing with wear graph. All of the nomenclatures used in this research are given in Table 1.

Table 1. The nomenclatures used in the research.

F_n	Normal force	$2k$	Point angle
f_n (mm rev^{-1})	Feed rate	v	Tangential cutting velocity
i	Inclination angle	τ	Web length- to diameter ratio
$k_{n,t}$	specific cutting pressure	T	Cutting lips torque
$2R$	Drill diameter	b	Cutting length
r	radial distance of an element on the cutting lips	α_n	Normal rake angle
T_l	Cutting lips thrust force	t_c	Uncut chip thickness
2_w	Web thickness	N	Spindle speed(rpm)

Finally, an intelligent system with two inputs of feed motor current and spindle motor current is proposed to predict the wear values during the machining process, using fuzzy logic technique. The simulation results presented with MATLAB software show the effectiveness of fuzzy logic system for on-line tool wear monitoring in drilling operations.

Material and methods

Dynamical models of force for a new drill

In order to obtain the thrust and cutting force values in a drilling process, various researches have been carried out by many ofthe researchers all over the world. Yang et al. (2002) developed a method for modeling the dynamical forces in a new drill and predicted the thrust and cutting forces in drilling process, using of analytical models. Chandrasekharan et al. (1995) developed another method to predict cutting force in drilling process based on analytical and empirical models. In this research, dynamical models developed by Chandrasekharan et al. (1995) are used to predict thrust and cutting forces in drilling process. The most commonly used drill is the conventional conical point drill (Figure 1) and the models developed by Chandrasekharan et al. (1995) are applied for this drill only.

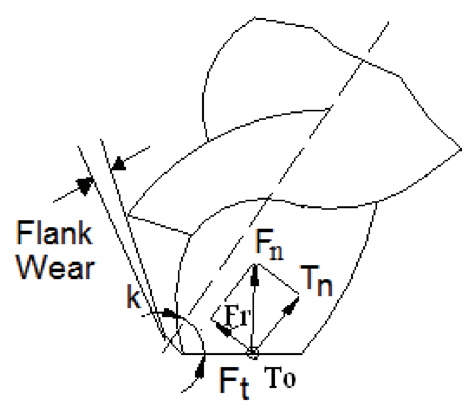

Figure 1. Conical point drill.

For a new drill, the experiments have been conducted on an OKUMA(MC-4VAE) CNC machining center Akistler (9273 A) by Chandrasekharan et al. (1995). Four-channel dynamometer has been used to measure the thrust and torque forces. Material used is gray cast iron and a HSS drill has been used for drilling the material. Data has been sampled at 100 Hz and stored in a pc. Table 2, shows the machining parameters used in this paper (CHANDRASEKHARAN et al., 1995).

Table 2. Experimental data of thrust force and torque (CHANDRASEKHARAN et al., 1995).

Feed (mm/rev)	Speed (rpm)	Diameter (mm)	Point angle	Web thickness (mm)	Pilot hole diameter (mm)	Cutting lips		Total chisel		Entire drill	
						Thrust (N)	Torque (Nm)	Thrust (N)	Torque (Nm)	Thrust (N)	Torque (Nm)
0.229	400	15.9	118	2.3	3.2	1091.5	13.52	1037	1.29	2228	14.8
0.102	200	15.9	118	2.3	3.2	661.5	7.31	629	0.548	1352	8.63
0.102	800	15.9	118	2.3	3.2	574.8	6.85	503	0.505	1149	7.36
0.254	400	12.7	118	2.3	2.8	953.0	9.34	863	0.919	1873	10.2
0.102	400	9.5	118	1.5	2.4	373.5	2.7	393	0.356	811	3.06
0.102	400	12.7	118	2.3	2.8	490	4.9	510	0.7	1000	5.7
0.102	400	15.9	135	2.3	4.4	539.8	4.42	299	0.468	868	6.86
0.178	400	9.5	118	1.5	2.4	525.4	8.11	743	0.601	1376	8.72

To find an analytical model, experimental evidence has shown that the dependence of the specific cutting pressures on the chip thickness and cutting velocity is well described by equation (1).The specific cutting pressures can then be written as (CHANDRASEKHARAN et al., 1995).

$$K_{n,t} = \alpha_0 t_c^{\alpha_1} v^{\alpha_2} e^{\alpha_3 \alpha_n} \quad (1)$$

As mentioned above, to develop an analytical-empirical model for the chisel and lip edge, Chandrasekharan et al. (1995) used experimental data to find the constant values in equation (1). Then by using the specific cutting pressures in formula (2, 3) and integrating, the thrust torque and cutting torque in lip edge of the drill are estimated respectively.

$$K_l = F_n sink = \int_{\tau}^{1} 2k_n(\rho)\frac{f}{2} sinkcosi(\rho)Rd\rho \quad (2)$$

$$T_0 = \int_{\tau}^{1} 2k_t(\rho)\frac{f}{2} R\rho cosi(\rho)Rd\rho \quad (3)$$

Also to develop an analytical model for chisel edge the same equation is used in logarithmic form As: [11].

$$lnK_n(r) = lna_0 + \alpha_1 lnt_c + \alpha_2 \left\{ ln\left(\frac{2\pi N}{60}\right) + lnr \right\} + \alpha_3 \alpha_n \quad (4)$$

$$lnK_t(r) = lnb_0 + b_1 lnt_c + b_2 \left\{ ln\left(\frac{2\pi N}{60}\right) + lnr \right\} + b_3 \alpha_n \quad (5)$$

By using the above equations along with the experimental data, the values of constants are estimated. Again the specific cutting pressures are integrated over the entire length of the chisel edge to obtain the thrust and the cutting torque developed at the chisel edge. To develop an analytical model, all of the dynamical force equations have been applied to make a block diagram model in MATLAB software (Figure 2).

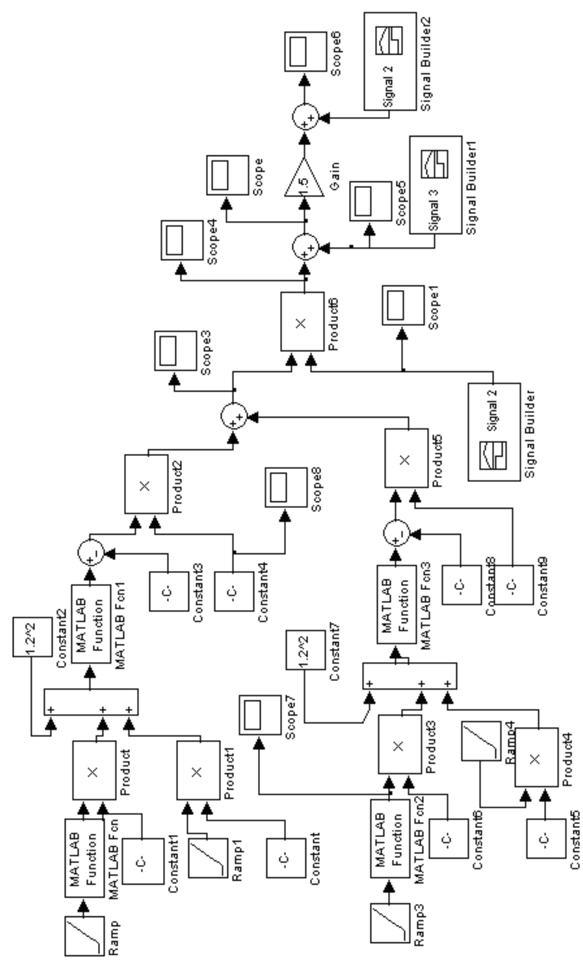

Figure 2. Block diagram of dynamical thrust and cutting forces.

Tool wear model

In general, during the machining process tool wear impairs the sharpness of the cutting edges, increases the friction between the tool and work piece, and increases the power consumption. In order to obtain the value of Thrust and cutting forces in a worn drill, the wear model must be developed. To reach to this purpose, different works have been carried out by several researchers. Salimi and Zadshakouyan (2009) simulated the wear block diagram for a single point tool that estimates the amount of flank wear rate on the flank edge. In this model, the state equations of the wear are developed and the values of constants are estimated by experimental results. In this paper, the wear model based on Carrillo and Zadshakoyan (1997) research is used to obtain the value of wear for a worn drill as:

$$\dot{X}1 = \alpha K2Cw(X1 + X2 + X3) + K2F_0 \tag{6}$$

$$\dot{X}2 = \frac{1}{\tau}(K_0F_0 - X2) \tag{7}$$

$$\dot{X}3 = \alpha K1Cw(X1 + X2 + X3) \tag{8}$$

$$F_C = F_0 + bCwW_f \tag{9}$$

where:

K_0, K_1, K_2C_w, *a* are the model constants that are related to machining conditions. The block diagram of the model is given in Figure 3.

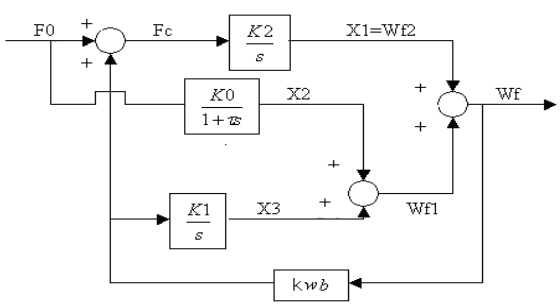

Figure 3. Block diagram of the wear model Carrilo and Zadshakouyan (1997).

In the above model, X1 is diffusion wear, X2: initial wear, X3: linear wear, *Wf1*: composed of two initial and linear wear, *Wf2*: is diffusion wear that increases relevant to the temperature. F_0, is the cutting force and F_C is the total force of the both new and worn drill. S, in this model is the Laplace variable.

Machine tool drive system

To obtain the relationship between tool wear and motor current, developing the block diagram of the machine tool drive is necessary. The block diagram of the simulated machine tool drive system is given in Figure 4. In drilling operations, as drill wear begins, thrust and cutting force values are raising proportionally.

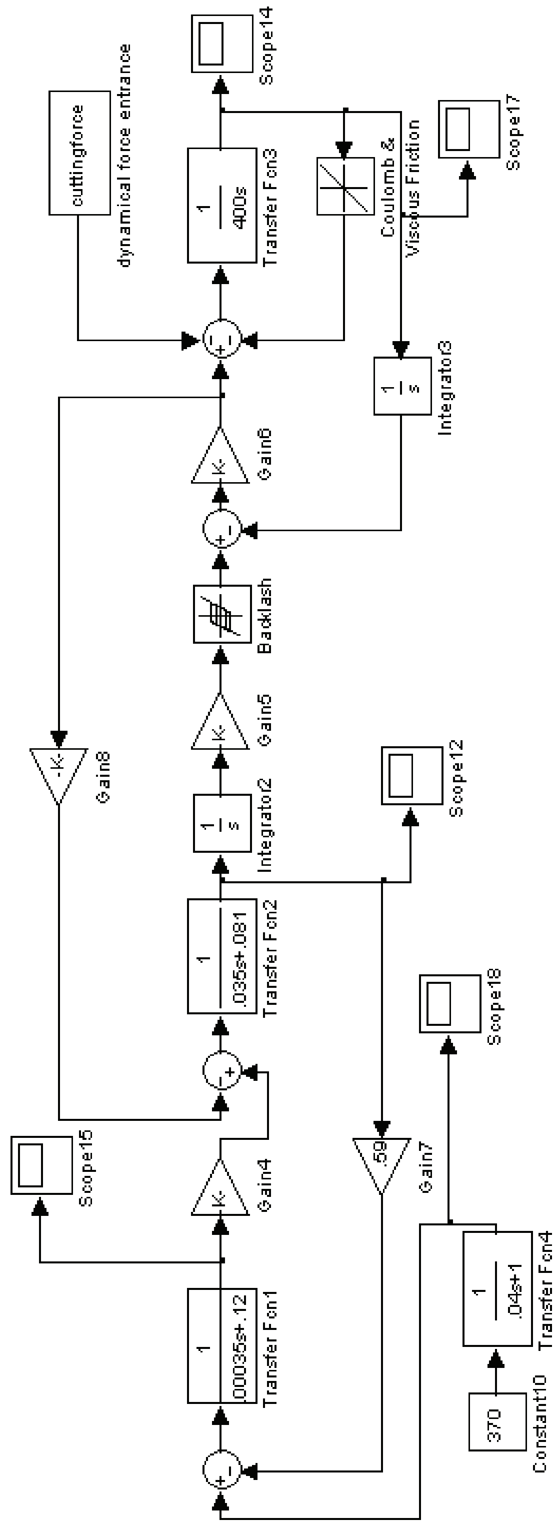

Figure 4. Simulated block diagram of feed drive for the IHU3 type of motor.

On the other hand it makes the motor current value to increase. During the machining process, if the cutting tool cannot withstand the increased cutting forces, tool failure becomes inevitable and motor current shows a dramatic changes. Therefore, there is a straight relationship between force and motor current. To establish a model for this relationship, developing the machine tool drive system is necessary to estimate the motor current during the process that has been carried out by some researchers (DESFORGES; ARCHIMÈDE, 2006; HUANG et al., 2007). Desforges and Archimède (2006) analyzed and developed block diagram of machine tool drive that is used in this paper for a special type of motor.

MATLAB simulations

Based on the previous issues discussed so far, the block diagram of the new drill and worn drill for estimating the cutting and thrust forces was simulated in this paper.

The block diagram of the cutting and thrust forces for the new drill was simulated using of SIMULINK tool box in MATLAB software. The simulation results given in Figure 5 show the changes in the values of forces during machining along the chisel and lip edges of the drill.

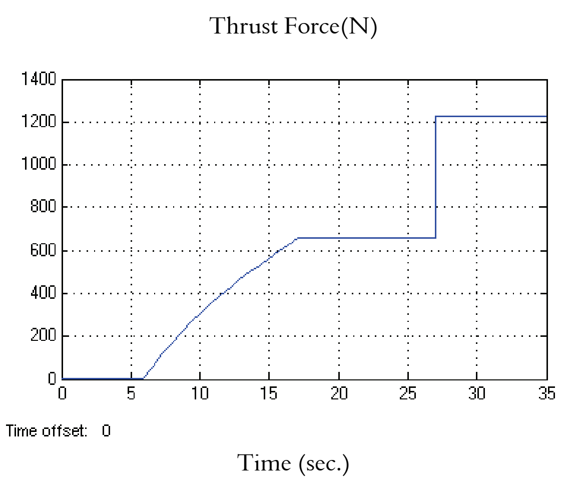

Figure 5. Simulated thrust force diagram for a new drill: diameter 15.9 mm, point angle118°, helix angle 33°, pilothole diameter 3.2 mm, speed 200 rpm, federate 0.102 mm rev^{-1}.

As mentioned before, the block diagram of the drill wear model was simulated and the results are seen in Figure 6 that shows the wear rate and the force values for the worn drill.

The results extracted from the simulated block diagram of the feed drive system for the machine tool are given in Figure 7.

As is seen in the Figure 4, the input for the block diagram of machine tool is cutting force and the output is the motor current that is predicted based on the cutting force.

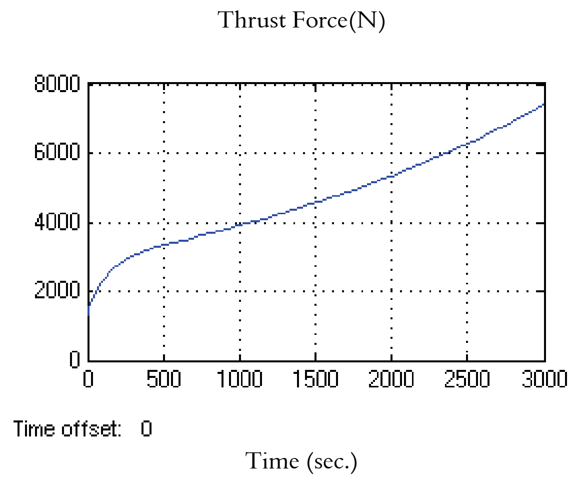

Figure 6. Simulated thrust force diagram for a worn drill: diameter 15.9 mm, point angle 118°, helix angle 33°, pilot hole diameter 3.2 mm, speed 200 rpm, federate 0.102 mm rev^{-1}.

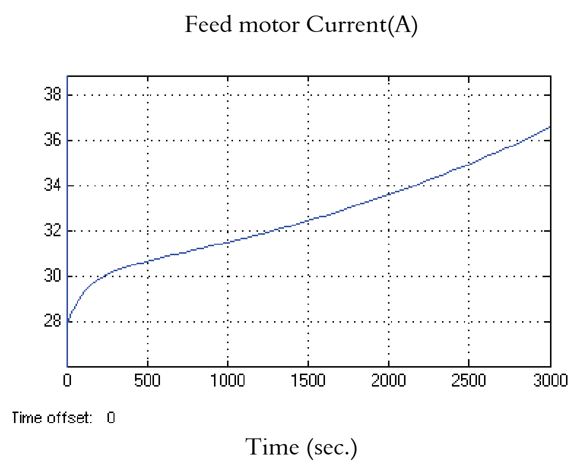

Figure 7. Simulated feed motor current diagram during drilling: diameter 15.9 mm, point angle118°, helix angle 33°, pilot hole diameter 3.2 mm, speed 200 rpm, federate 0.102 mm rev^{-1}.

Fuzzy logic

Zadeh (1996) introduced fuzzy logic for the first time in 1965. Fuzzy logic is a major development of fuzzy set theory. This is a multi-valued logic that allows intermediate values to be defined between conventional evaluations like yes/no, black/white, etc. In contrast with traditional logic theory, where binary sets have two-valued logic: true or false, fuzzy logic variables may have a truth value that ranges in degree between 0 and 1. Fuzzy logic has been extended to handle the concept of partial truth, where the truth value may range between completely true and completely false. Furthermore, when linguistic variables are used, these degrees may be managed by specific functions. In other words, fuzzy logic was designed to represent and reason with knowledge in linguistic or verbal form.As an extension of the case of multi-valued logic, valuations (u: $v_0 \rightarrow w$) of propositional variables (v_0) into a set of membership degrees (w) can be thought of as membership functions mapping predicates into fuzzy sets (or more formally, into an ordered set of fuzzy pairs, called a fuzzy relation). With these valuations, many-valued logic can be extended to allow for fuzzy premises from which graded conclusions may be drawn.

Decisions in fuzzy systems are based on inputs in the form of linguistic variables. The variables trigger, or 'fire', a certain number of IF-THEN rules, which produce one or more responses (conclusions) depending on which rules are fired. The conclusion of each rule is weighted according to the degree of membership of its inputs. Usually, the center of gravity of the responses is calculated to obtain an appropriate crisp output. The major advantages of the fuzzy logic approach are: i) a mathematical model is not necessary, ii) the knowledge base is formed by a set of practical rules using linguistic variables, and iii) this method is very efficient under uncertain conditions, which are common in everyday situations. According to Azadegan et al. (2011), Fuzzy tools provide a simplified platform where the development and analysis of models require reduced development time than other approaches.

Fuzzy logic modeling

For prediction the wear rate in this research, fuzzy logic toolbox in MATLAB software was used. The fuzzy inference system predicts the amount of drill wear due to the changes in motor currents. Two parameters including the spindle and feed motor currents were given to the fuzzy model as inputs and the value of drill wear rate was determined as output. In order to obtain an accurate result, all of the existed membership functions in MATLAB, were tried and the best function was used for fuzzy modeling. In this research Mamdani method was applied to design the fuzzy logic model and the Trapezoid and Triangular membership functions are selected. After giving the inputs and outputs to the model, the rule base system must be designed to control the system. As mentioned previously in this paper, knowledge base or rule base system is designed based on the experimental data. The larger the number of experiments the more accurate results will be obtained. In this research, the number of rules is 36 by which the input and output are connected to each other. Figure 8 shows the fuzzy logic model in which the spindle and feed motor current values are as inputs, and wear rates are as output. The membership function of the wear is seen in Figure 9.

w_1 in Figure 9 is the minimum wear rate in which, the tool is assumed to be sharp and $w_8$is the maximum wear rate in which, the tool is supposed to be worn out and breakage probability is very high. The wear region is divided to 8 small regions. The wear rate for the new drill is taken between 0 and 0.15 mm and the wear rate for a worn drill are taken between 0.8 and 1 mm.

When the wear rate reaches to 0.8 mm it means that the tool must be changed with a new drill. The wear rate of 0.8 mm is only used for HSS drills and for the carbide tools the tool life is taken less than 0.35 mm. The wear rate obtained from the analytical model is then compared with the estimated wear rates obtained from fuzzy model. As seen in Figure 10 the results show that there is a closeness compromise between the results as the value of $R^2$of regression graph is 0.9367.

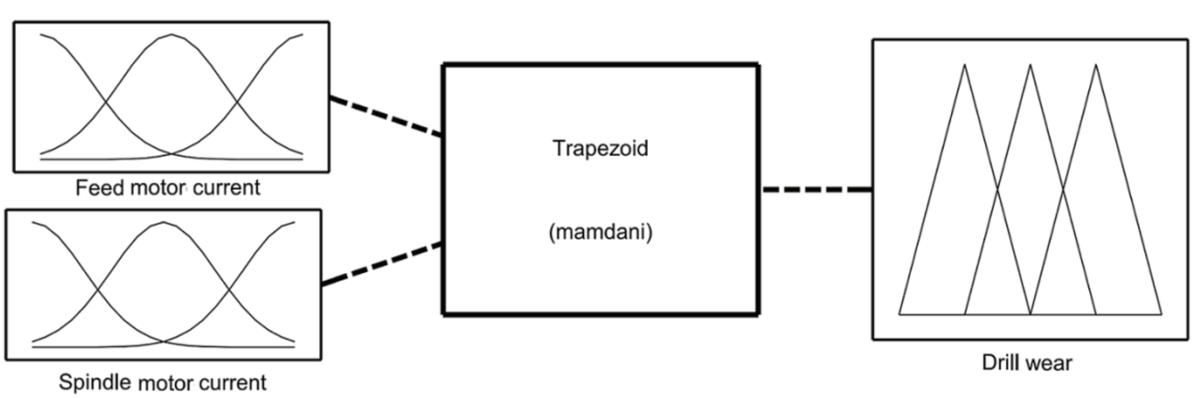

Figure 8. Fuzzy logic model.

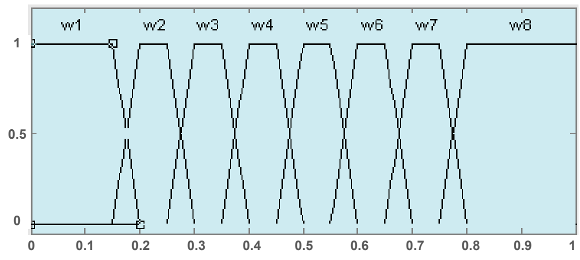

Figure 9. Membership function of the wear rate.

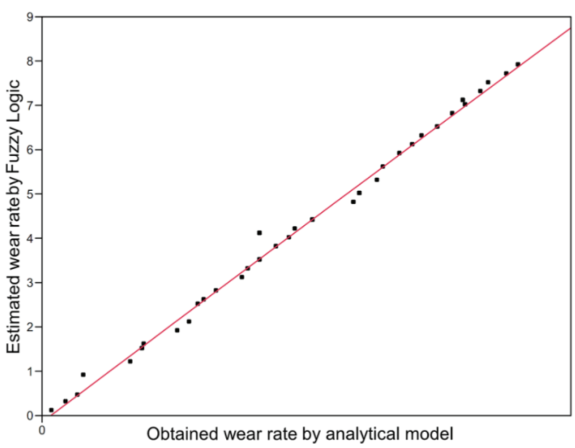

Figure10. Comparison of the wear rate obtained from fuzzy logic and analytical model.

Results and discussion

In this paper an intelligent system for drill wear prediction is proposed. For this purpose, first the analytical and empirical models of cutting and trust forces are used to simulate the dynamical forces in lip and chisel edges of the drill. Then a wear model is used to predict tool wear rate in any arrangements and also machine tool drive block diagram is used to predict feed and spindle motor current rate. Finally the data were investigated by a fuzzy logic system and the results compared to each other.

Instead of the machine tool in this paper, block diagram of the machine tool used to predict the amount of motor current. For this purpose three models including thrust and cutting force block diagram, tool wear model block diagram and machine tool drive system block diagram are connected to each other to give the motor current changes in relation to the cutting and thrust force of the drill during drilling process. As is shown in Figure 6 and 7 there is a relationship between cutting forces and motor current. Any increase in wear rate causes a raise in cutting force and motor current in machining process. The fuzzy logic model applied for drill wear prediction is a reliable method based on the simulation results in Figure 10. Also it shows that by applying this prediction model in machining process, the prediction process can be carried out practically only by applying the machining parameters in the model.

Conclusion

Predicting and monitoring of the drill wear rate by using of feed and spindle current motor is possible and can be applied widely in adaptive control systems to prevent drill wear failure. Also, the fuzzy logic system is an important and effective tool to investigate and predict the nonlinear incidents, like tool wear, in machining systems. This is confirmed by comparing the measured and estimated values with each other in which the value of R^2 was obtained 0.9367 in the regression graph.

Using of analytical models and control system of machine tool is one of the specifications of this paper that can be used even as a sensor less method to detect and monitor the machining process. In the case of facing with any problem during the machining process the current behavior can be analyzed and followed through system block diagram.

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